THE IMPACT OF HIGH ENERGY DENSITY CAPACITORS WITH METALLIZED ELECTRODE IN LARGE CAPACITOR BANKS FOR NUCLEAR FUSION APPLICATIONS

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Summary

Power supplies for Inertial Confinement Fusion (ICF) lasers require large capacitor banks. As capacitor bank size increases, reliability, expressed as Mean-Time-Between-Failures (MTBF) is reduced, for a given capacitor design. Metallized electrode capacitors exhibit more predictable failure characteristics than traditional foil designs, thus increasing MTBF for some applications. In addition, their "soft" failure mode gives facility operators flexibility to schedule capacitor bank maintenance.

Experience with the design and testing of a metallized electrode capacitor for a 13 MJ bank is presented. Weibull statistics are used to predict performance on the 13 MJ bank, and on a proposed 250 MJ facility. While the Beamlet capacitor data is specific to Aerovox capacitor part number KM223YW215D01, much of the information is applicable to high voltage metallized electrode capacitors in general.

Introduction

LLNL has built a succession of increasingly larger ICF laser facilities since 1971. The lasers provide 1 to 10 ns pulses to drive fusion targets for energy and weapons research.

The existing Nova facility employs a 55 MJ capacitor bank including 2600 capacitors, each storing 12.5 kJ, and 7000 capacitors each storing 3 kJ. The capacitors are operated at 20 kV to 22 kV, in parallel circuits of 20 kJ to 40 kJ each. The discharge pulse from each circuit is roughly 6 kA, with a pulse length of 800 us. The load for the bank is 5000 xenon flashlamps in the Nd:glass laser amplifiers. The facility has been in operation since 1984, has accumulated some 5000 shots and presently experiences a capacitor MTBF of roughly 150 shots.

The Beamlet laser is presently under construction and will be completed in 1994. It is powered by a 13 MJ capacitor bank, made up of 256 individual 52 kJ circuits similar in design to Nova, but with only one capacitor per circuit. The output pulse from each capacitor is 13 kA peak, and 500 us wide, with less than 10% reversal.

The Beamlet is designed to demonstrate the laser technology required to build the proposed National Ignition Facility. This facility, to be constructed jointly by several Department of Energy contractors, is designed to achieve ignition of a fusion target in the laboratory. It requires a 250 MJ capacitor bank arranged in circuits similar to those in the Beamlet capacitor bank. Since this will be a large, stationary facility, the size and weight of the capacitors bank are of little importance. Therefore, the primary criteria used to choose capacitors for the NIF will be cost and reliability.

Metallized electrode capacitor have evolved over the last decade to their present state where they are capable of providing many of the attributes needed for large capacitor banks. The electrodes for these capacitors are a few hundred angstroms thick and are vapor deposited on a film of dielectric material. The electrodes are thin enough to see through. This type of capacitor can be designed for high energy density, high reliability, high system fault tolerance, high reversals, and relatively high peak currents. Perhaps the most endearing quality of the capacitors is the way that they fail. Instead of becoming a short circuit and receiving bank fault energy, the capacitors slowly lose capacitance. The loss of capacitance results from the loss of electrode as the capacitor goes through the normal dielectric fault and fault clearing process which occurs when the fault current attempts to drive through the metallized electrode. Millions of such clearings occur before a capacitor reaches the defined end of life.

Design Impact of Metallized Electrode Capacitors

The self-healing properties of the metallized electrode dielectric system results in a substantial impact in ICF capacitor bank design. The contributing factors are improved life characteristics, higher density and a "soft" failure mode. The cost of the capacitors is roughly the same as for discrete foil designs with an equivalent characteristic lifetime.

The improvement in life characteristics is primarily due to a reduction in the number of early, or "infant mortality" failures in a large bank. In previous ICF facilities, the effect of early failures was minimized by choosing capacitors with characteristic lifetimes much longer than the expected bank life, and performing extensive burn-in tests. The 12.5 kJ capacitors developed for Nova, for instance, have a characteristic life of 213,000 shots, while the bank life is 5,000 to 10,000 shots. In addition, each capacitor received a 500 shot burn-in test at elevated voltage conditions in an attempt to weed out units prone to early failure. Since early failures are minimized with metallized electrodes, burn-in test requirements are significantly reduced.

The "soft" failure mode of the metallized capacitors becomes an advantage during operation of the laser facility. Since the primary mode of failure is a gradual reduction

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in capacitance, facility operators can choose when to replace capacitors by defining the end of life consistent with the facility requirements. For example, as in ICF banks, if many capacitors are connected in parallel to a common load, a small reduction in capacitance of one unit may have a negligible effect on the system operation. This capability results in a reduction in operating costs, since a capacitor failure seldom results in unplanned down time. On a user facility such as the NIF, the savings would be substantial, since each missed shot represents substantial lost revenue to the operators. Although the dominant failure mode is gradual, catastrophic failures can occur if the winding arcs to the capacitor case. Therefore, protective measures such as fuses for large parallel banks are still required. In the Beamlet facility, provisions were made to measure the peak current of each circuit on every shot. This data can be archived and plotted over many shots to identify capacitors that are beginning to fail.

Additional advantages of the self-healing design are increased energy density and higher manufacturer yield. The increased density reduces the total size and weight of the capacitor bank, and simplifies handling and lifting.

The combination of reduced size and increased yield, compared with foil designs, help offset the increased material cost associated with the metallized dielectric.

Capacitor Design Considerations

The design work for the capacitor used in Beamlet began at Aerovox in the late 1980s where a small IR&D effort yielded a successful technology demonstrator. Work on this effort and similar high energy density capacitors has resulted in the development of engineering parameters that allows the design of capacitors with consistent and highly predictable characteristics. The performance of the capacitors under normal operating conditions, overvoltage conditions, fault conditions, or any combination thereof can be determined for any given set of conditions prior to building full sized capacitors. The accuracy of the predictions can be tracked during normal use by monitoring the capacitance change.

For the final design of the Beamlet capacitors, small scale capacitors were built and tested to determine the rate of degradation for the capacitors. The resultant data is shown in Figures 1 & 2 where the rate of degradation of capacitance was predicted to be 0.16%/1000 shots under normal conditions and 1%/1000 shots under fault conditions. The nominal rate of degradation, shown in Figure 3, is very close to this. Since only 25 fault shots were run on the qualification capacitors, it is difficult to determine if the large scale capacitor performance is the same as the small scale capacitors but it can be said that there was no unusual degradation measured as a result of the qualification fault current testing. This ability to demonstrate performance on a small scale level results in highly accurate predictions of capacitor performance under any set of conditions with low cost experiments.

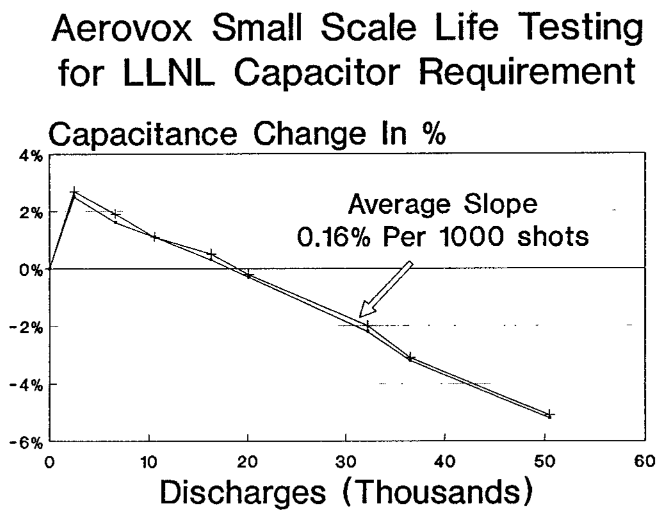

Figure 1

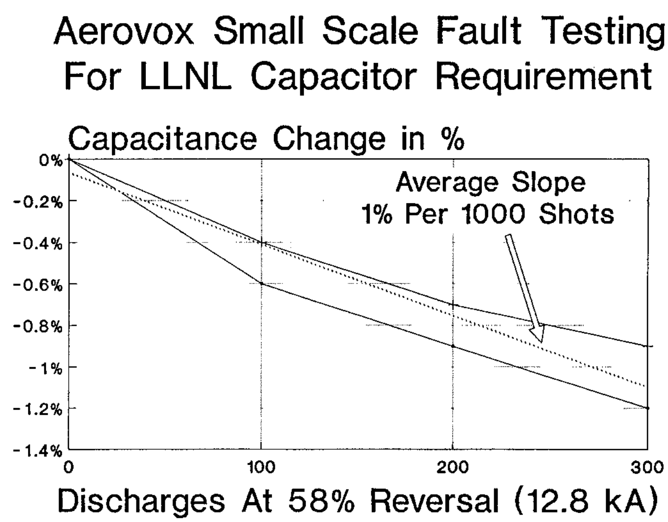

Figure 2

Performance on Beamlet Tests

The Beamlet project requires 256 dual-bushing capacitors, storing 52 kJ each with a 22 kV charge. The requirement is that the bank survive 10,000 shots at full energy before significant maintenance is required. Qualification and acceptance tests were performed to assure reliable bank operation. For these tests, end of life was defined as a 5% reduction in capacitance from the nominal (215 μF) value.

The qualification tests were performed on three capacitors, and included a 10,000 shot test at full voltage and current, plus 25 fault mode tests. The fault mode test is equivalent to the flashlamp load shorting at the beginning of the pulse. The peak current and reversal were 22 kA and 67% respectively. The capacitance was measured with an electronic bridge every 1000 shots, and the test was continued past the defined end of life. The results of these tests are shown in Figure 3. Scatter in the data are the result of limited measurement resolution and capacitor temperature fluctuations.

LLNL Prototype Test of Beamlet Capacitors

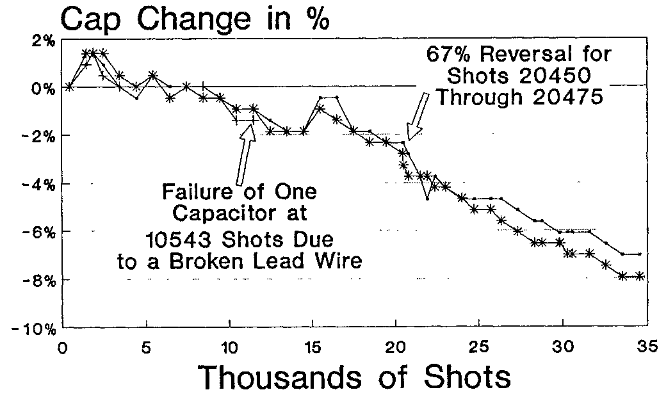

Figure 3

Acceptance testing was performed on 300 capacitors delivered in lots of roughly 45 units each. Each capacitor received an initial capacitance measurement, a bushing-to-case hi-pot test at 25 kV for one minute and a 25 shot burn-in at full normal operating conditions. The capacitance was re-measured to identify problems. Three capacitors from each lot were then subjected to a 1000 shot test. The capacitance was measured every 250 shots, and an extrapolation made to 10,000 shots to predict whether the capacitor would fail. One of the three was then tested to the full 10,000 shots. Any one failure resulted in re-testing of three additional capacitors from that lot. Any two failures would result in rejection of the entire lot. No failures were found, however one of the 10,000 shot tests came close to failing and resulted in a re-test. The data are shown in Figure 4.

LLNL Acceptance Test of Aerovox Capacitors

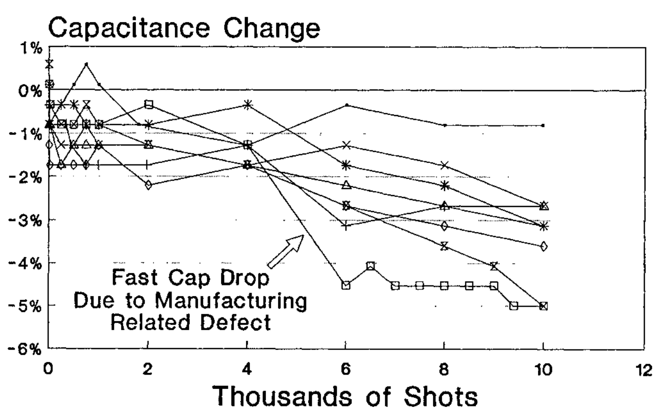

Figure 4

The fault current testing done on the Beamlet capacitors is well within the capacitor's fault capability and not enough shots were accumulated on any one capacitor to show the expected degradation of Figure 2. Aerovox did testing on similar capacitors using more severe fault conditions. Two capacitors rated 22 kV, 50 kJ, were tested at 22 kV, with 80,000 amps peak fault current and 80% voltage reversal. (1) The data from the testing, shown in Figure 5, indicates a controlled rate of degradation, or loss of capacitance, of 18% per 1000 shots under these fault conditions.

Aerovox TESTING OF TYPE KM 50 kJ, 22 kV, 1 MJ/m^3 CAPACITORS at 81,500 Amps and 80% Reversal

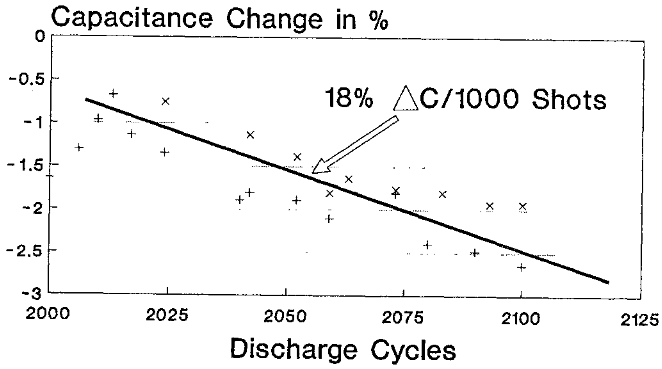

Figure 5

The combined test data from qualification and acceptance were analyzed using Weibull statistics. The resulting Weibull function parameters are shown in Table 1 compared with the Nova capacitors. The large shape parameter results from the absence of early failures. The Weibull function can be used to predict MTBF for the bank by estimating the percentage of failures as a function of cycles. The advantage of the large Weibull shape parameter is illustrated by Figures 5a and 5b. The relative constant failure rate of the Nova capacitors during the life of the Beamlet capacitors is shown by the cumulative distribution functions plotted in Figure 6a. The expanded scale of Figure 6b, shows that for a bank lifetime below 6000 shots, the Beamlet capacitors are more reliable.

Weibull Stastics Comparison of Nova and Beamlet Capacitor Banks

	Beamlet (52 kJ)	Nova (12.5 kJ Scaled to Beamlet Size)
Bank Size (MJ)	13	55
Energy Density (Joules per cm^3)	0.9	0.25
Weibull Slope	3.4	1.1
Weibull Characteristic Life	19,700	213,000
Predicted MTBF (5000 Shots)	2100	316
Predicted MTBF (10000 Shots)	412	293
Actual MTBF	--TBD--	360

Table 1

Cumulative Weibull Distribution Function Over 30,000 Bank Shots

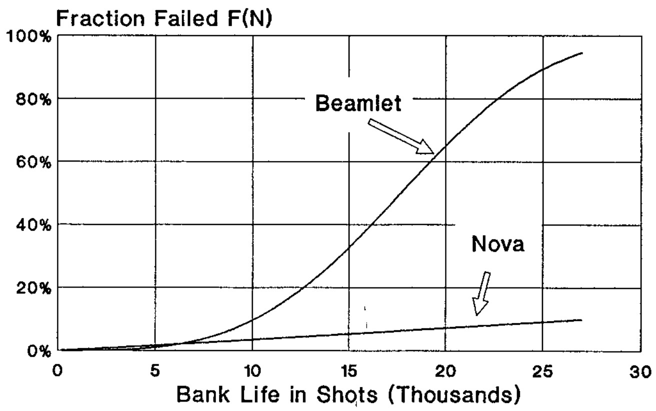

Figure 6a

Cumulative Weibull Distribution Function Over 8,000 Bank Shots

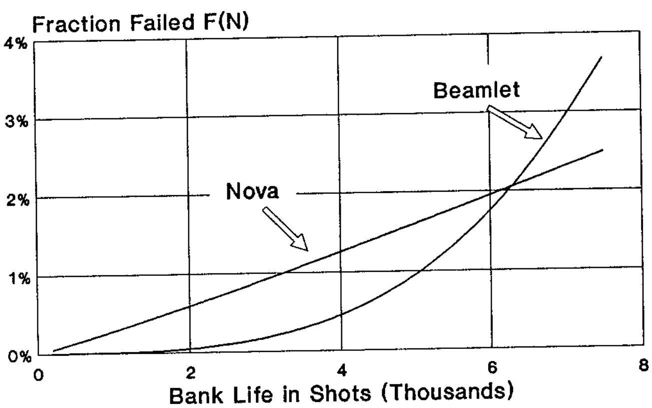

Figure 6b

MTBF is by definition a constant but it will change if the defined life of the bank is changed. MTBF vs. the defined bank life plots are shown in Figure 7 for the Beamlet and NIF banks based on the Beamlet capacitor data.

MEAN TIME BETWEEN FAILURES for BEAMLET CAPACITORS

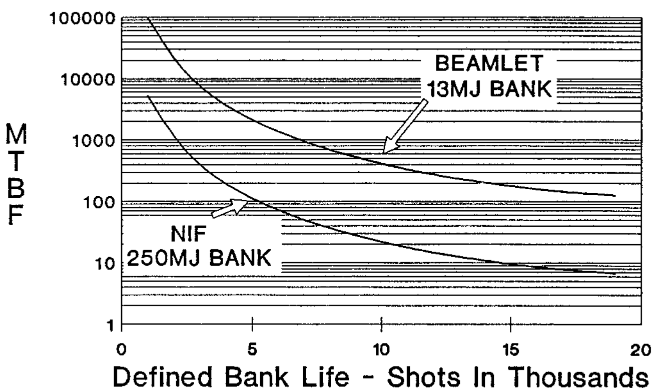

Figure 7

Conclusions

The self-healing properties of metallized electrode capacitors represent a significant advantage over discrete foil designs in large capacitor banks for ICF. A Weibull statistics analysis indicates that a reasonable MTBF is achieved without significantly over-designing the capacitor for a given application. The highly predictable performance of the capacitors allow for accurate scaling from an individual pad to a capacitor or from a capacitor to a bank. Operational convenience represents another significant advantage. Experience with Beamlet will determine whether Weibull statistics accurately describe capacitor bank life characteristics.

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